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# Observation of SCS decay $D^{+,0} \to \omega\pi$ and branching fraction measurement of $D^0 \to K^0_S K^+ K^-$


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Using a data set of 2.92 $\text{fb}^{-1}$ of $e^+e^-$ collisions at the $\psi(3770)$ mass accumulated with the BESIII experiment we present preliminary results from our study of the singly Cabibbo-suppressed decays $D \to \omega\pi$ and the decay of $D^0 \to K^0_S K^+ K^-$. The decay $D^+ \to \omega\pi^+$ is observed for the first time with a significance of $5.4\sigma$ and we find evidence of $4.1\sigma$ for the decay $D^0 \to \omega\pi^0$. As a cross-check the branching fraction $D \to \eta\pi$ is measured and is found to be compatible with the current PDG value. The branching fraction of the decay $D^0 \to K^0_S K^+ K^-$ is measured in an untagged analysis with $11743 \pm 113$ signal events and is found to be $(4.622 \pm 0.045(stat.) \pm 0.181(sys.)) \times 10^{-3}$. This is compatible with previous measurements but with significant improved precision.



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# 1 Introduction

We present two measurements of $D$ meson branching fractions. Both analyses aim to determine branching fractions precisely and are therefore relevant to improve theoretical predictions of other branching fractions and/or of the $D^0$ mixing parameters. The search for the decays $D \to \omega\pi$ and its comparison with theoretical predictions furthermore provides an insight to SU(3) symmetry in $D$ decays. The analysis of the decay $D^0 \to K_S^0 K^+ K^-$ is a step towards a strong phase determination in this channel, which in turn is important in the determination of the CKM angle $\gamma$ via the GGSZ method[1] in $B^+ \to D^0 h^+$ decays.

BESIII is a $4\pi$ detector with a geometrical acceptance of 93% and consists of the following components. The momentum and energy loss of charged tracks are measured in a small-cell helium based multilayer drift chamber in a 1T magnetic field. The relative momentum resolution for a 1 GeV track is 0.5 %, and its energy loss is measured with a precision of 6 %. The chamber has a radius of 81 cm and is surrounded by a time of flight system built of two layers of plastic scintillator which is capable of measuring the flight time of particles with an accuracy of 80ps in the barrel and 110ps in the end caps. This provides a K$\pi$ separation of $2\sigma$ for a 0.9 GeV track. Around the time-of-flight system, 6240 CsI(Tl) Crystals measure the energy of electromagnetic showers with a relative resolution of $2.5\%/\sqrt{E}$ and their position with $0.6\,\mathrm{cm}/\sqrt{E}$. Finally, surrounding the superconducting coil of the magnet are 9 layers of resistive plate chambers for muon identification. Further details can be found in [2].

BESIII has collected a large data sample at $\sqrt{s} = 3.773\,\mathrm{GeV}$ in $e^+e^-$ collisions with an integrated luminosity of 2.92 fb$^{-1}$. At this energy pairs of charged and neutral $D$ mesons are produced by the decay of the $\psi(3770)$ in a quantum-correlated state. Since the additional phase space doesn't allow for another hadron the sample provides a very clean environment to study $D$ decays.

We present preliminary results for observation of the singly Cabibbo-suppressed decay $D \to \omega\pi$ and the branching fraction measurement of $D^0 \to K_S^0 K^+ K^-$.

# 2 Observation of the SCS decay $D^{+,0} \to \omega\pi$

The precise measurement of singly Cabibbo-suppressed decays is challenging since usually statistics are low and background is high. Therefore the clean environment of $D$ decays at the $\psi(3770)$ is ideal to search for and study these decays. The decays of neutral and charged $D$ mesons to the final state $\omega\pi$ has not been observed yet, but a theoretical calculation exists that predicts the decay at a level of $1 \times 10^{-4}$[3]. CLEO-c failed in a previous analysis to reach that precision and provided a consistent upper limit of $3.0 \times 10^{-4}$ and $2.26 \times 10^{-4}$ @90 % C.L. (including $\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)$) for charged and neutral $D$ decays respectively[4].

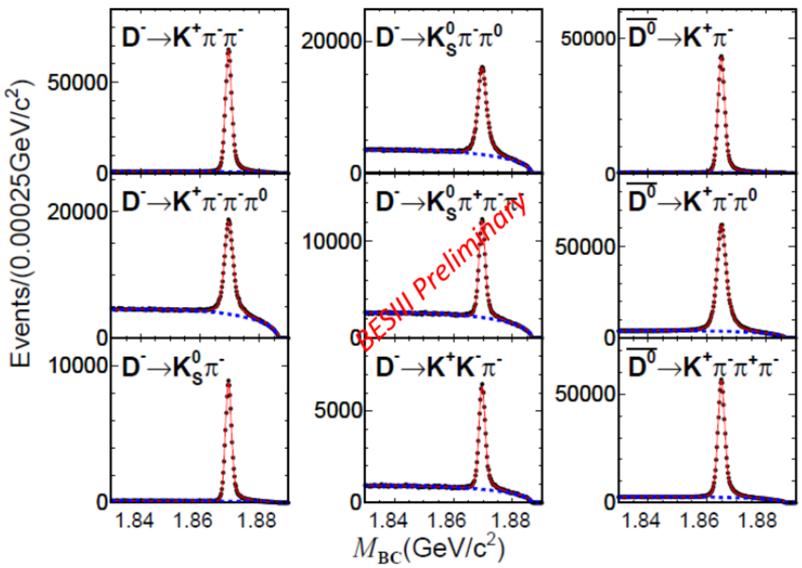
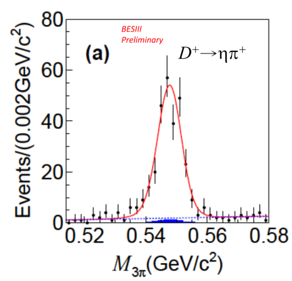



Figure 1: Beam-constraint mass distributions for all tag modes.

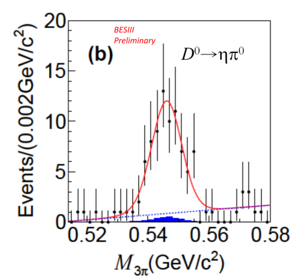
With its larger statistics ($\sim 3\times$ CLEO-c), BESIII is able to reach the precision of the theoretical prediction. As a cross-check we also extract the branching fractions $D^+ \to \eta\pi^+$ and $D^0 \to \eta\pi^0$.

## 2.1 Reconstruction and selection

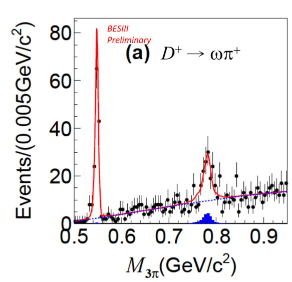
We measure the branching fraction using the so-called double-tag method, which was originally developed by MARKIII[5]. We reconstruct one $D$ meson in a generic way using a set of decay modes with high branching fractions and low background contamination. We use 6 different modes for the charged $D$ decay and 3 for the neutral decay. The reconstructed candidates are required to have an energy compatible with the beam energy within approximately $3\sigma$. If multiple candidates exist the candidate with an energy closest to the beam energy is selected.



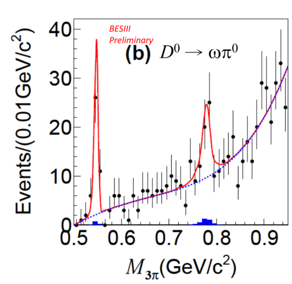

(a) $D^+ \to \eta\pi^+$




(b) $D^0 \to \eta\pi^0$




(c) $D^+ \to \omega\pi^+$




(d) $D^0 \to \omega\pi^0$

Figure 2: Invariant mass distribution $\pi^+\pi^-\pi^0$.

The beam-constraint mass distributions $m_{BC}$* for all tag modes are shown in Fig.1. From a fit to these distributions with an ARGUS[6] background function and a signal shape that includes effects from ISR, the $\psi(3770)$ line shape and detector resolution, we obtain $1\,462\,041 \pm 1359$ and $2\,234\,741 \pm 2425$ tag candidates for the charged and neutral $D$ decays respectively.

In events in which a tag candidate is found we search for the final states $D^+ \to (\pi^+\pi^-\pi^0)_{\omega/\eta}\pi^+$ and $D^0 \to (\pi^+\pi^-\pi^0)_{\omega/\eta}\pi^0$. Again we select the candidate with the energy closest to the beam energy if multiple candidates exist. Two combinations are possible the assign the $\pi^+/\pi^0$ and the wrong combination is almost completely excluded by a requirement on the invariant $3\pi$ mass. The double tag technique highly suppresses background from continuum background ($q\bar{q}$). To also suppress the remaining $D\bar{D}$ background we require that the helicity $H_\omega$† of the $\omega$ is larger $0.54(D^+)$ and $0.51(D^0)$. Further we apply a $K_S^0$ veto to suppress background from $D^{+,0} \to K_S^0\pi^+\pi^{0,-}$. A 2D signal region in the beam-constraint mass of tag and signal decay is defined. The $(\pi^+\pi^-\pi^0)_{\omega/\eta}$ invariant mass distribution is shown in Fig.2(c)(d).

| | N | $N^{bkg}$ | $N^{obs}_{sig}$ |
|---|---|---|---|
| $D^+ \to \omega\pi^+$ | $98 \pm 15$ | $22 \pm 4$ | $76 \pm 16$ |
| $D^0 \to \omega\pi^0$ | $40 \pm 11$ | $4 \pm 8$ | $36 \pm 14$ |
| $D^+ \to \eta\pi^+$ | $262 \pm 17$ | $6 \pm 2$ | $256 \pm 18$ |
| $D^0 \to \eta\pi^0$ | $71 \pm 9$ | $3 \pm 2$ | $68 \pm 10$ |

Table 1: Signal and background yields.

## 2.2 Background and signal yield

The signal yield is extracted from the $3\pi$ invariant mass. The $\omega/\eta$ signal shape is taken from MC and convoluted with a Gaussian to take differences in resolution between data and MC into account. In case of the $\eta$ peak the width is a fit parameter, and for the $\omega$ we use the $\eta$ width scaled with a factor taken from MC. The combinatorial background is described by polynomials. The 'raw' yield $N_{\omega/\eta}$ includes a small component of peaking background from the continuum process $e^+e^- \to (\omega/\eta) + (n\pi)$. We extrapolate events from sideband regions to the signal

| Source | $\omega\pi^\pm$ | $\omega\pi^0$ | $\eta\pi^\pm$ | $\eta\pi^0$ |
|---|---|---|---|---|
| $\pi^\pm$ tracking | 3.0 | 2.0 | 3.0 | 2.0 |
| $\pi^\pm$ PID | 1.5 | 1.0 | 1.5 | 1.0 |
| $\pi^0$ reconstruction | 1.0 | 2.0 | 1.0 | 2.0 |
| 2D $M_{\rm BC}$ window | 0.1 | 0.2 | 0.1 | 0.2 |
| $\Delta E$ requirement | 0.5 | 1.6 | 0.5 | 1.6 |
| $\|H_\omega\|$ requirement | 3.4 | 3.4 | – | – |
| $K_S^0$ veto | 0.8 | 0.8 | – | – |
| Sideband regions | 0.5 | 6.7 | 0.0 | 0.5 |
| Signal resolution & shape | 0.9 | 0.9 | 4.3 | 5.4 |
| Background shape | 3.3 | 2.0 | 2.0 | 3.2 |
| Fit range | 0.6 | 1.9 | 0.8 | 1.1 |
| $\mathcal{B}(\omega(\eta) \to \pi^+\pi^-\pi^0)$ | 0.8 | 0.8 | 1.2 | 1.2 |
| Overall | 6.1 | 8.8 | 6.1 | 7.3 |

Table 2: Systematic uncertainties.

*Beam-constraint mass is defined as $m_{BC}^2 = E_{\rm beam}^2 - p_D^2$. With the reconstructed $D$ momentum $p_D$ and the beam energy $E_{\rm beam}$.

†The helicity $H_\omega$ is defined as the angle between the $\omega$ decay plane and the direction of the $D$ meson in the $\omega$ rest frame.

| Decay mode | This work | Previous measurements[8] |
|---|---|---|
| $D^+ \to \omega\pi^+$ | $(2.74 \pm 0.58\,(\text{stat.}) \pm 0.17\,(\text{sys.})) \times 10^{-4}$ | $< 3.4 \times 10^{-4}$ @90 %C.L. |
| $D^0 \to \omega\pi^0$ | $(1.05 \pm 0.41\,(\text{stat.}) \pm 0.09\,(\text{sys.})) \times 10^{-4}$ | $< 2.6 \times 10^{-4}$ @90 %C.L. |
| $D^+ \to \eta\pi^+$ | $(3.13 \pm 0.22\,(\text{stat.}) \pm 0.19\,(\text{sys.})) \times 10^{-3}$ | $(3.53 \pm 0.21) \times 10^{-3}$ |
| $D^0 \to \eta\pi^0$ | $(0.67 \pm 0.10\,(\text{stat.}) \pm 0.05\,(\text{sys.})) \times 10^{-3}$ | $(0.68 \pm 0.07) \times 10^{-3}$ |

Table 3: Preliminary results for the branching fractions D$\to \omega\pi$ and D$\to \eta\pi$.

region and subtract the number of background events to obtain the number of signal decays $N_{\text{sig}}^{\text{obs}}$. The yields are summarized in Tab.1.

### 2.3 Systematics and results

The major source of systematic uncertainties arise from differences between data and MC. The overview of all contributions is shown in Tab.2. The main contributions come from charged track reconstruction as well as from the requirement on the $\omega$ helicity. The helicity distribution is shown in Fig.3. The distribution for data follows the expected distribution of the P$\to$VP decay ($\sim \cos^2\theta$). Further significant contributions come from signal and background shapes.

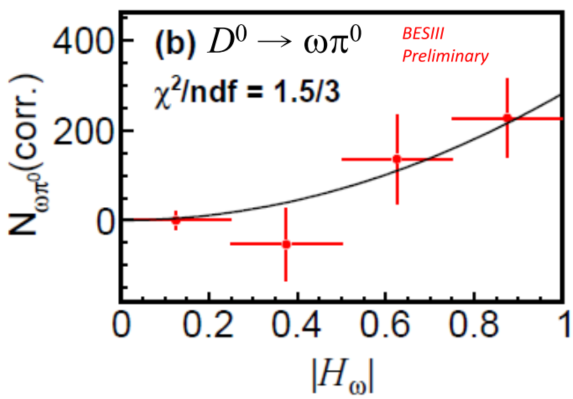



Figure 3: Helicity distribution $D^0 \to \omega\pi^0$.

The resulting preliminary branching fractions are listed in Tab.3. We are able to observe the decay of charged $D$ mesons to the final state $\omega\pi^+$ with a significance of $5.4\sigma$ and we find evidence for the neutral $D$ decay to $\omega\pi^0$ at the $4.1\sigma$ level. As a cross-check the branching fractions $D \to \eta\pi$ are also measured for the neutral and charged $D$ decay. The results are in good agreement with the current PDG[7] values.

## 3 Branching-fraction $D^0 \to K_S^0 K^+ K^-$

A *BABAR* measurement[8] is the basis of the current PDG[7] value:

$$\Gamma(D^0 \to K_S^0 K^+ K^-)/\Gamma = (4.47 \pm 0.34) \times 10^{-3} \quad (1)$$

Since the decay was measurement in the reaction $D^* \to D^0\pi^\pm$ only a relative normalization is possible (in that case relative to $K_S^0\pi^+\pi^-$), the precision is only 7.6 %.

With the large statistic sample at BESIII of $\psi(3770) \to D\overline{D}$ we can measure the branching fraction of the decay with absolute normalization, which in turn reduces the uncertainty. Furthermore an analysis of $D^0 \to K_S^0 K^+ K^-$ Dalitz plot is ongoing.

## 3.1 Reconstruction and selection

Due to the quantum-correlation of $D^0$ and $\overline{D}^0$ a branching fraction measurement using the double tag method is very difficult. It would require knowledge of the mixing parameters and the ratio of DCS to CF decays for all tag channels. Therefore we reconstruct the signal decay untagged.

The $K_S^0$ is reconstructed in the channel $K_S^0 \to \pi^+\pi^-$ and our final state is therefore $K^+K^-\pi^+\pi^-$. We require that the kaon tracks come from the interaction point and pass criteria for particle identification. The $K_S^0$ candidate is furthermore required to have a significant flight distance. All tracks are fitted with the constraint to make the $D^0$ mass.

The distribution in $K_S^0$ mass and beam-constraint mass $m_{BC}$ for all selected signal candidates is shown in Fig.4. We determine the signal yield by a 2D fit in $K_S^0$ mass and beam-constraint mass $m_{BC}$. According to a simulation study the background consists mainly of $q\bar{q}$ events.

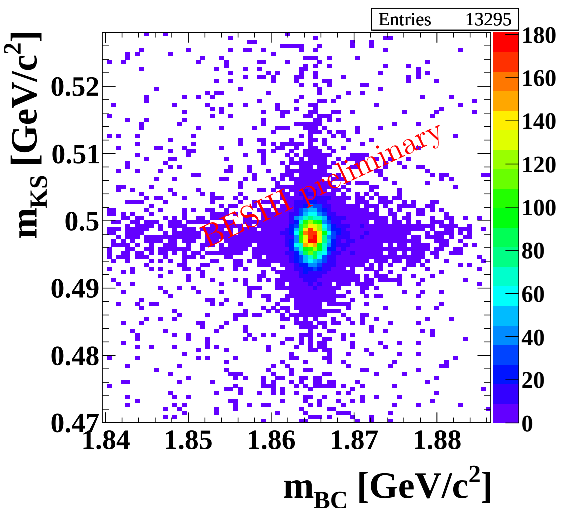



Figure 4: Selected candidates.

## 3.2 Efficiency

The efficiency of reconstruction and selection is obtained on a inclusive MC sample by the same fitting procedure as on data. This ensures that potential biases cancel in the branching fraction ratio. The projection of the MC sample and the fitted model is shown in Fig.5. We obtain a

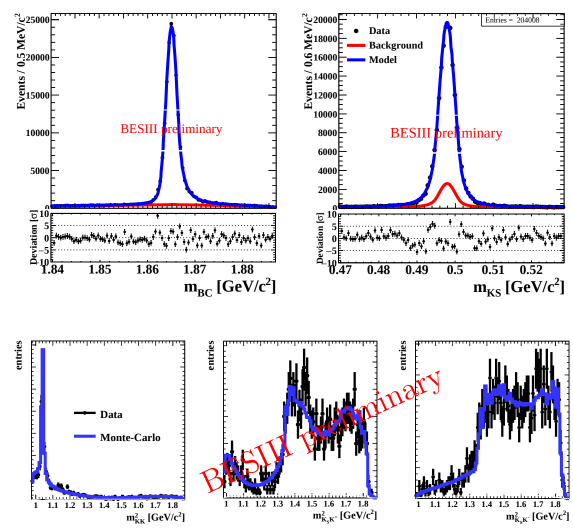



Figure 5: Projections of fit to inclusive MC sample(top) and Dalitz plot projections of signal model(bottom).

value of $(0.1719 \pm 0.0004)$. The efficiency is not constant over whole phase space, which leads to a dependence on the MC amplitude model. However our signal amplitude model is in adequate agreement with data so that we can neglect this source of systematic uncertainty.

### 3.3 Systematics and results

The systematic uncertainties on the branching fraction are listed in Tab.4. The largest contributions arise from charged track reconstruction and identification of $K^{\pm}$ and from the uncertainty of the cross-section measurement $e^+e^- \to D^0\overline{D}^0$. The total systematic uncertainty is below 4 %.

The branching fraction can be calculated by:

$$\mathcal{B}_{D^0 \to K_S^0 K^+ K^-} = \frac{N^{sig}}{\epsilon_{BF} \cdot \mathcal{B}_{K_S^0 \to \pi\pi} \cdot \mathcal{L} \cdot 2\sigma_{D^0\overline{D}^0}} \tag{2}$$

The cross-section $e^+e^- \to D^0\overline{D}^0$ measured by CLEO-c[9] is $(3.66 \pm 0.07)$ nb and for the branching fraction $K_S^0 \to \pi^+\pi^-$ the PDG[7] average is used:

Our preliminary result for the branching fraction $D^0 \to K_S^0 K^+ K^-$ is:

$$BF_{data}(D^0 \to K_S^0 K^+ K^-) = (4.622 \pm 0.045\,(\text{stat.}) \pm 0.181\,(\text{sys.})) \times 10^{-3} \tag{3}$$
$$\tag{4}$$

The total uncertainty is 4 % which is an improvement of the PDG value by almost a factor of 2. The agreement with the PDG value is better $1\sigma$.

## 4 Summary

We present preliminary results from studies of hadronic charm decays. We present the first observation of the decay $D^+ \to \omega\pi^+$ with a branching fraction of $(2.74 \pm 0.58\,(\text{stat.}) \pm 0.17\,(\text{sys.})) \times 10^{-4}$ and find evidence for the decay $D^0 \to \omega\pi^0$ with a branching fraction of $(1.05 \pm 0.41\,(\text{stat.}) \pm 0.09\,(\text{sys.})) \times 10^{-4}$. Furthermore we measured the branching fractions $D^{(+,0)} \to \eta\pi^{(+,0)}$ in good agreement with the PDG average.

The decay $D^0 \to K_S^0 K^+ K^-$ is studied using an untagged method and a preliminary branching fraction of $(4.622 \pm 0.045\,(\text{stat.}) \pm 0.181\,(\text{sys.})) \times 10^{-3}$ is obtained. The measurement is the first absolute measurement and reduces the uncertainty of this branching fraction by almost a factor of 2. An analysis of the Dalitz plot is currently ongoing.

| Systematic uncertainties [%] | |
|---|---|
| PDF shape | 0.20 |
| selection | 0.80 |
| Efficiency | |
| statistics | 0.33 |
| PID ($K^+K^-$) | 2.00 |
| tracking | 2.00 |
| $K_s^0$ reconstruction | 1.50 |
| External | |
| Luminosity measurement | 1.00 |
| cross-section $e^+e^- \to D^0\bar{D}^0$ | 1.83 |
| $K_s^0$ BF | 0.07 |
| Total | 3.92 |

Table 4: Systematic uncertainties.

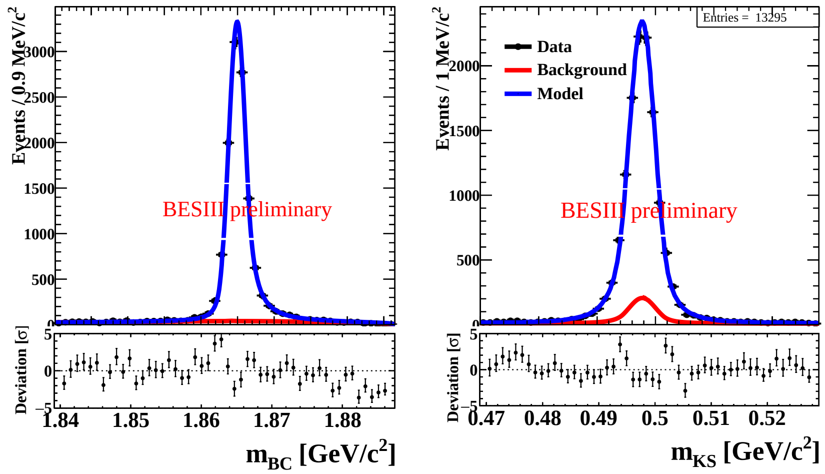



Figure 6: Projections of fit model and data sample.

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